Mechanical Behavior of Dam Foundation with Vertical Sand Drain, Case Study: Sombar Dam

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Abstract. Installing vertical sand drains is a traditional dam foundation consolidation solution that is economical and provides good drainage efficiency. Vertical sand drains can shorten the path of water flow inside the soil and speeds up soil consolidation. This study investigated the effect of sand drains in the foundation of the Sombar Dam in Iran on its mechanical behavior. The Sombar Dam is a project to control flooding and provide agricultural water to Gholaman city in northeastern Iran. The investigation included the mechanical behavior of the dam with vertical sand drains. The studied parameters were drain diameter, depth and spacing in addition to the vertical-to-horizontal permeability ratio (ky/kx) of the foundation soil during the time of construction of the dam using a Mohr-Coulomb (MC) model in the software application GeoStudio. The results revealed that reducing the drain spacing (increasing the number of drains) and increasing the depth and diameter of the drains led to an increase of the settlement rate (up to 90%) and the stability of the dam over a shorter period of time (24 months) compared to no drain condition. With a decrease in the ratio of vertical-to-horizontal permeability (ky/kx = 0.1) for all drain parameters there was a decrease in the value of the dam settlement rate and the safety factor.

Keywords: *earth dam; safety factor; sand drain; saturated soft soil; settlement; Sombar Dam.*

1 Introduction

Staged construction is a cost-effective technology that is widely used in the construction of low fills and earth dams over soft ground [1]. Embankments constructed on soft soil with a high groundwater level show excessive settlement and require a long time duration to dissipate the excess pore pressure. In such instances, ground improvement measures are often used to enhance stability and to decrease the consolidation period [2]. Soft clay has a low bearing capacity and high compressibility features. Thus, it is necessary to apply improvement techniques prior to construction to avoid unacceptable differential settlement [3]. To increase the soft soil shear strength, using vertical drains for preloading of soft clay is a commonly used method, which can also

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be used to control post-construction settlement. Various types of vertical drains are applied and have been studied in the literature, including gravel piles, geosynthetic vertical drains, and sand drains [4]. The consolidation process is shortened by the installation of vertical drains during and after the construction period, so the maximum safety factor can be achieved earlier. Also, the drains decrease the post-construction settlement of the embankment and the embankment settles more uniformly [2]. A combination of vertical drains with vacuum plus preloading is an effective method for speeding up the consolidation of the soil [5]. The variation of the safety factor (increase) over time is primarily influenced by the rate of dissipation of excess pore pressure within the soil depth up to which the critical slip surface passes [2].

Field soil settlement behavior can be predicted based on the plane strain conditions and the elastoplastic material behavior in a coupled analysis [6]. In [7], the settlement of an embankment predicted by the finite element method was slightly lower than of the settlement recorded in the field because the soil permeability decreased with an increase of the effective stress, which had not been properly accounted for in the analysis. The Mohr-Coulomb model (MC), or linear elastic-perfectly plastic model, is one of the most commonly used pressure-sensitive constitutive models. It can provide a suitable estimation of the structural behavior while only modest computational expenditure is required [8]. Mohr-Coulomb models are used in numerous engineering applications owing to their simplicity and easily determinable model parameters. Experimental strength values match well with the Mohr-Coulomb model predictions, but the strains predicted by the Mohr-Coulomb model are generally conservative [9].

Based on a review of vertical drains, smear phenomena have a considerable effect on the horizontal permeability (kx) of vertical drains. It has been observed that the possible mechanisms of shear phenomena are affected by the installation process and equipment, the type and nature of the soil in which vertical drains of different types are to be installed, and on the geometrical properties of the drains, such as the spacing, diameter and depth of penetration [10]. The diameter of the smear zone (ds) can be estimated as two to three times the equivalent mandrel diameter (dm) and ds = 3dm is suggested when no test data are available [11]. A detailed laboratory investigation is useful for determining the geotechnical design parameters for analysis of consolidation with prefabricated vertical drains [12]. Radial flow to a central drain involves a cylinder of soil around a single vertical drain with simplified boundary conditions, or axisymmetric water flow in analytical modeling. In a two-dimensional (2D) finite-element analysis with a plane-strain model, it is necessary to convert the system of vertical drains to an equivalent drain wall [13].

Using GeoStudio (2012) and a Mohr-Coulomb model, the current study investigated the effect of a vertical sand drainage system on the mechanical behavior of the Sombar Dam underlined by soft saturated clay for different arrangements and vertical-to-horizontal ratios of permeability.

2 Work Methodology

2.1 Dam Location and Geometry

The study area is located in northeastern Iran, in the northern part of Khorasan province, adjacent to the border between Iran and Turkmenistan. The dam is located exactly 2 km from the asphalt road between Gholaman city and Castle village. The data used in this investigation were taken from the final report on geotechnical studies of the Sombar Dam. The core of the dam has a symmetrical gradient of 1:0.4 (V:H). The core of the barrier has been positioned along the length of the contact with the supports. Figure 1 presents the geometry of the Sombar Dam [14].

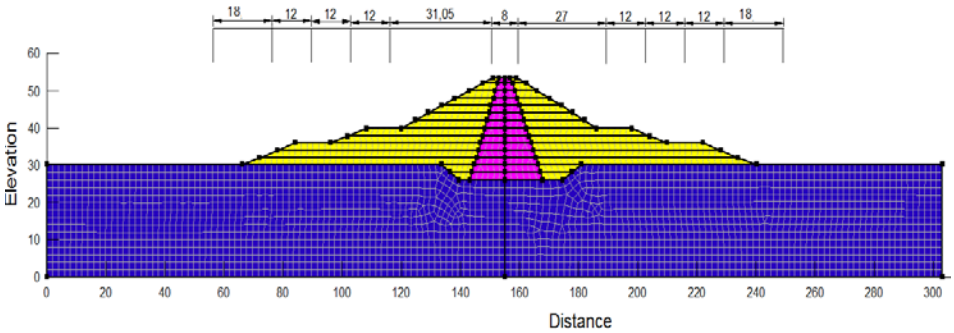


Figure 1 Geometry of the Sombar Dam [14].

2.2 Soil Characterization

Based on the final report on geotechnical studies of the Sombar Dam, it can be categorized as an earth limestone dam with a clay core and sandy crust. The site of the dam is mostly fine-grained alluvium with coarse-thick layers up to 30 meters wide across the valley. This fine-grained alluvium is classified CL-ML, CL, and sometimes ML, and the coarse aggregates are classified as SC, SC-SM, SM according to the unified soil classification system (USCS). The groundwater level is around 4 m from ground level.

The coefficient of consolidation (Cv) is $2.25*10^{-3}$ cm^2/sec under a vertical stress of 2 kg/cm^2, $1.1*10^{-3}$ cm^2/sec under 4 kg/cm^2 and $1*10^{-3}$ cm^2/sec under 8 kg/cm^2. Table 1 shows the soil properties in the dam and foundation [14].

Table 1 Soil properties of the dam and foundation [14].

Soil type	Test method	Unit weight, kN/m^3	E, kPa	υ	C, kPa	Φ, degree	k, m/sec
Clay core	UU	20	22900	0.48	80	0	10^{-9}
	CU		22900	0.48	45	15	
	CD		19100	0.25	32	27	
Sandstone	-	22	40000	0.2	42	42	10^{-5}
Fine-grained foundation	CU	19	1416	0.48	14	14	10^{-9}

2.3 Modelling of the Vertical Drains

SIGMA/W, SLOPE/W and SEEP/W, sub-software programs of GeoStudio (2012) [15], were used to perform the investigation of the case study. Based on the in-situ stresses, the initial stresses were calculated by applying the self-weight of the soil. Multiple analyses in GeoStudio (SIGMA/W and SLOPE/W in sequence) facilitated the modeling of staged construction (fill), where soil is added over time. The excess pore water pressure was considered in the analysis. Due to the length of the crown of the dam, a linearly elastic-perfectly plastic, or Mohr-Coulomb (MC), model was adopted in the analysis based on the actual conditions of the Sombar Dam. The relationship between strain and stresses in the Mohr-Coulomb model is completely linear to a point and after this point the stress-strain curve becomes a horizontal line.

SIGMA/W together with SEEP/W were used for a fully coupled consolidation analysis depending on equilibrium and equations based on elasticity theory and Biot's proposed equations. A hydraulic permeability function is proposed to dissipate the excess PWP. It should be noted that for the specification of materials based on the range of laboratory results, the combination is considered from the viewpoint of creating pore pressure in the dam body and foundation. The simplest method to consider the effect of vertical and radial consolidation is given in Eq. (1) based on Carillo [16].

$$(1-U) = (1-U_v)(1-U_h) \quad (1)$$

where U is the total average degree of consolidation, U_v is the average vertical degree of consolidation, and U_h is the average horizontal degree of consolidation.

Most over-drained drains have a trapezoidal shape and this trapezoidal surface can be close to the surface of the circle of an equivalent diameter. Thus, the diameter dw formed in a wall drain with width a and thickness b can be calculated by Eq. (2), as adopted from Indraratna, *et al.* [17].

$$d_w = \left(\frac{a+b}{2}\right) \quad (2)$$

The failure is expressed in GeoStudio as in Eq. (3) [15].

$$F = \sqrt{J_2}\sin\left(\theta+\frac{\pi}{3}\right) - \sqrt{\frac{J_2}{3}}\,\mathrm{cs}\left(\theta+\frac{\pi}{3}\right)\sin\emptyset - \frac{I_1}{3}\sin\emptyset - c\cos\emptyset \qquad (3)$$

When the angle of internal friction is zero, the criterion for collapse in the Mohr-Coulomb model in GeoStudio became as in Eq. (4) [15].

$$F = \sqrt{J_2}\sin\left(\theta+\frac{\pi}{3}\right) - c \qquad (4)$$

The investigation included the effect of sand vertical drains on the dam settlement and the upstream and downstream safety factor for different drain parameters. Drain depths (DD) of 8, 15, 18 and 24 m, drain spacings (DS) of 2, 3 and 4 m, drain diameters (DR) of 0.3 and 0.5 m in addition to soil coefficient of permeability ratios (ky/kx) of 1 and 0.1 were investigated. These parameters were studied within construction stages of 4, 8, 15 and 24 months and the height of the dam as a percentage of the final height for multiple analyses. Figure 2 shows the distribution of the drains in the foundation of the dam.

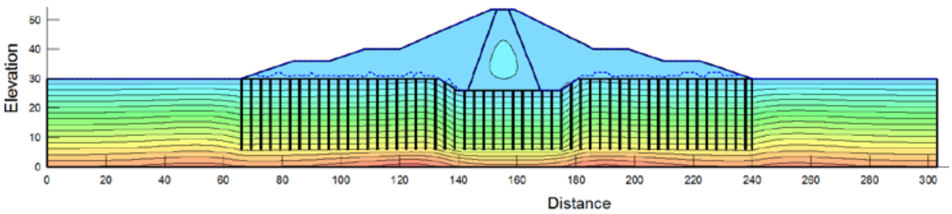
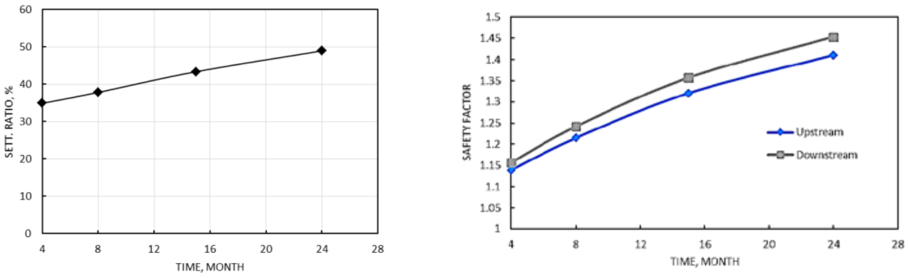


Figure 2 Diagram of the vertical sand drains.

3 Results and Discussion

3.1 No Drain Condition

Figures 3(a) and (b) represent the result of dam consolidation settlement ratio ($Sett_{time}/Sett_{final}$), SR, and factor of safety respectively versus time for no drain condition. The final total settlement was 0.9 m for the dam without drains. The settlement ratio (SR) varied in a linear trend and its maximum value was limited to < 50% after 24 months of construction. The safety factor (FS), both upstream and downstream, gradually changed (increased) with time; the maximum FS was 1.45 at the studied duration of construction (24 months). This situation may be related to the low water drainage. Figure 4 illustrates the failure upstream of the dam without drains produced by the software. The slip surface extended from the body of the dam to the foundation.



(a) Settlement (b) Safety Factor

Figure 3 Mechanical behavior of no drain condition.

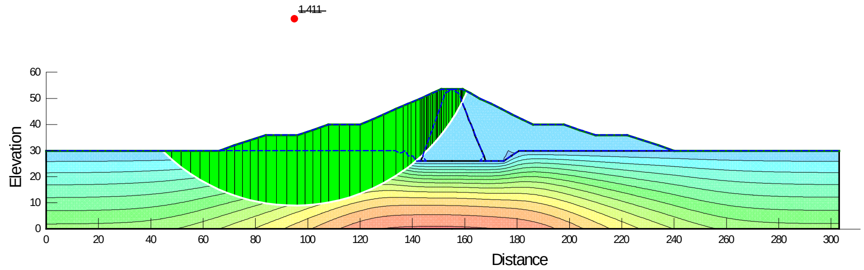


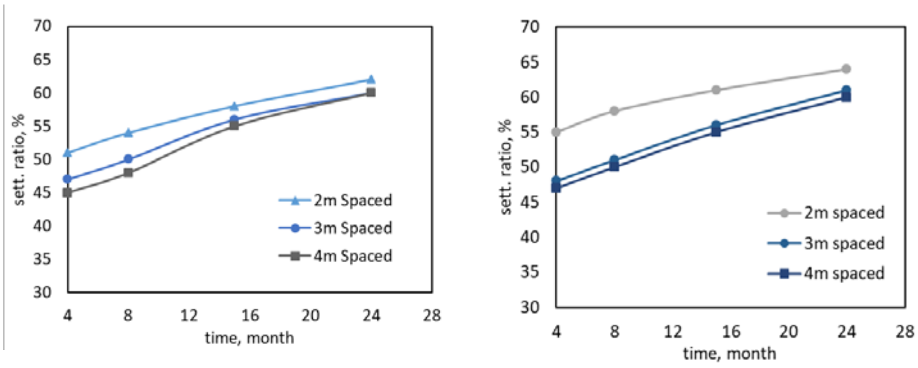
Figure 4 Upstream slope failure in MC model without drains after 8 months.

The investigation was extended to the mechanical behavior, decreasing the ratio of permeability to 0.1, resulting in a final consolidation settlement with a ratio of only 38% after 24 months, i.e. lower settlement due to a decrease in the vertical permeability. This decrease is also reflected in the safety factor, both upstream and downstream of the dam.

3.2 Effect of Drain Parameters

3.2.1 Settlement Behavior

Figures 5 shows the settlement ratio (SR) of the earth dam during construction for different parameters of the sand drains. An approximately linear SR-time relationship occurred in all studied cases and was most clear with the largest drain diameter (0.5 m). The settlement value was maximal with smaller spacing (2 m) and larger diameter (0.5 m). This behavior may be expected because of the faster water dissipation from the soil by the drains.

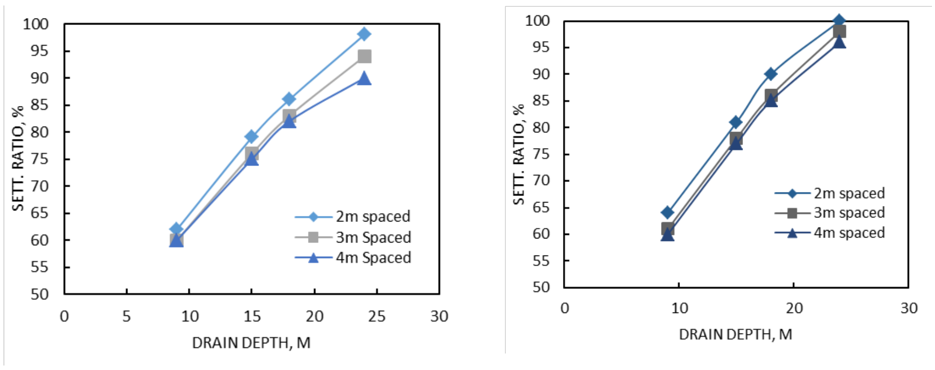


(a) 0.3 m diameter drain

(b) 0.5m diameter drain

Figure 5 Settlement ratio (Sr) versus time of dam construction for a drain depth of 9 m and different drain spacings and diameters.

The values of the settlement ratio from the different drain parameters became more convergent closer to the end of construction time of 24 months. To show the effect of the drain depth, Figures 6 shows the settlement ratio for different drain depths, spacings and diameters after 24 months of dam construction. It can be seen that there is a sharp convergent increase of both drain diameters until 18 m, after which a little divergence increase can be distinguished. The settlement ratio is increased from < 50% (no drain condition) to > 90% with a drain of 24 m deep, a spacing of 2 m and a diameter of 0.5 m at the end of construction (24 months).



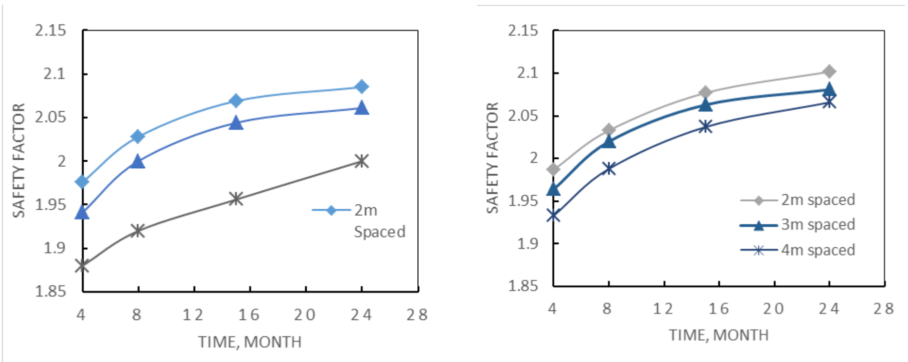
(a) 0.3 m diameter drain.

(b) 0.5 m diameter drain.

Figure 6 Settlement ratio (sr) versus time for drain depth with different drain spacings and diameters after 24 months of construction.

3.2.2 Behavior of Dam Safety

As for the settlement ratio, Figures 7 illustrates the upstream safety factor of the dam for different drain spacings and diameters versus construction time of the dam for a drain depth of 24 m. There is a significant increase in values with a clear gradual change over time. The values of the safety factor are in convergent condition; this behavior may be affected by the length of the sand drains (24 m). Figure 8 presents the failure of the dam upstream for specific drain conditions. The radius of the slip surface is increased with respect to no drain condition, i.e. an increase of the safety factor. Figures 9 presents the results of the behavior of the downstream safety factor. Similar to the behavior upstream, the increase trend of the values is in a gradual mode.



(a) 0.3 m diameter drain (b) 0.5 m diameter drain

Figure 7 Safety factor upstream versus time of dam construction for 24 m drain depth and different drain spacings and diameters.

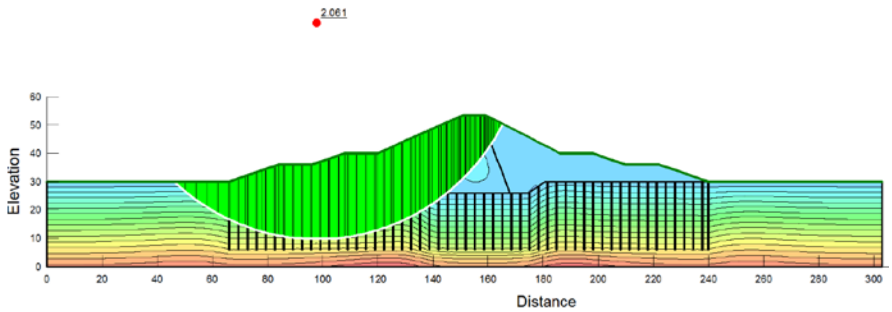
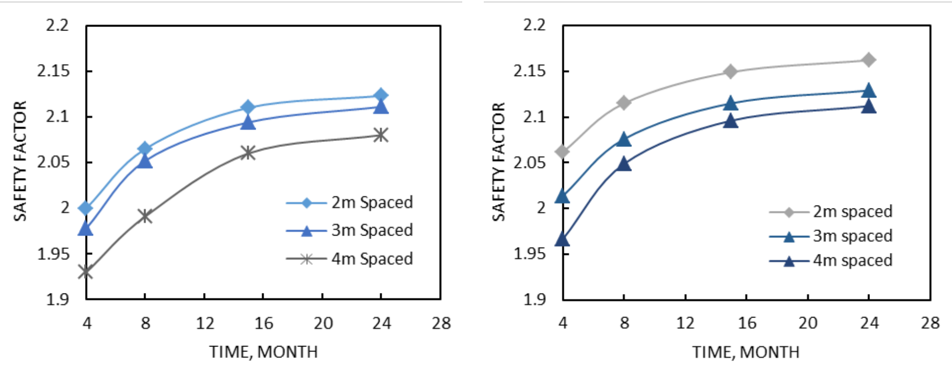


Figure 8 Upstream slope failure with sand drain of 0.3 m in diameter after 24 months.



(a) 0.3 m diameter drain (b) 0.5 m diameter drain

Figure 9 Downstream safety factor versus time of dam construction for 24 m drain depth and different drain spacings and diameters.

At the end of dam construction (24 months), the results of the safety factor match each other upstream and downstream regardless of the drain depth, as can be seen from Figure 10. The safety factor values demonstrate a major steep increase with respect to the behavior of no drain condition (DD = 0) up to DD = 18 m, whereas the FS values become constant. Figure 10 shows that the safety factor is increased from < 1.5 for no drain condition to > 2.0 for drain with a depth of 24m.

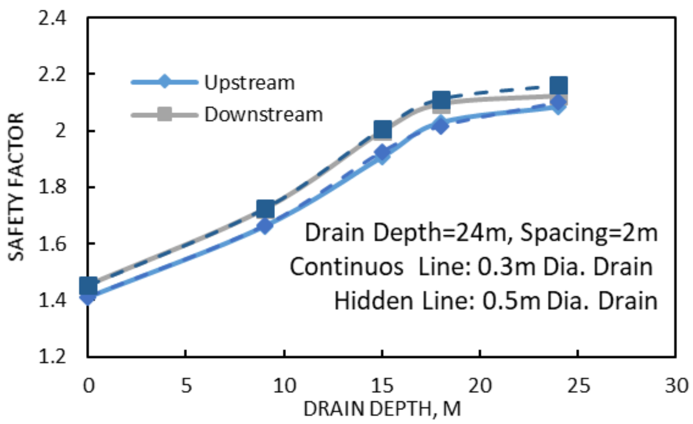


Figure 10 Downstream safety factor versus time of dam construction for different drain spacings and diameters.

3.3 Effect of Permeability Ratio (ky/kx)

To investigate the effect of the permeability ratio (ky/kx) on the results of the behavior of the dam on the soft clay with vertical sand, ky/kx values of 0.1 and 1 were adopted. Figure 11 indicates the settlement ratio for both cases for specific drain parameters. There is a gradual gentle decrease in SR values within the dam construction time, where ky/kx = 1.0 gives larger SR values. Figure 12 shows a comparison of the safety factor with respect to different permeability ratio (ky/kx) values. It can be seen that for the case of ky/kx = 1.0, the values of the upstream and the downstream FS of the dam have a constant trend, as mentioned before, while the FSs gradually increase for the permeability ratio of 0.1, i.e. a lower increase speed due the lower permeability in the vertical direction, as in the literature.

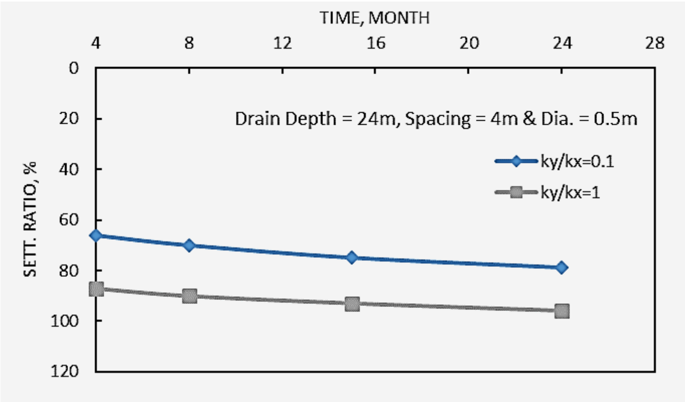


Figure 11 Settlement ratio versus time for different ky/kx values.

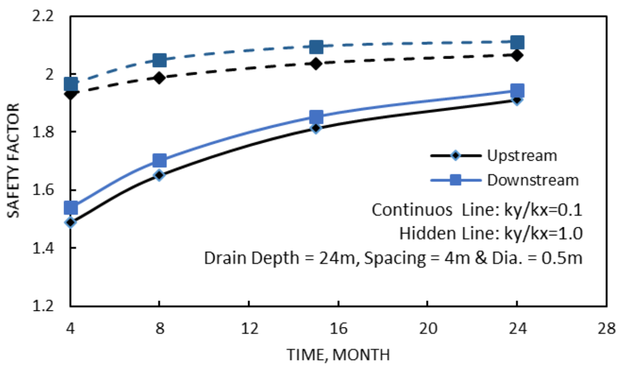


Figure 12 Upstream and downstream safety factors of the dam versus time for different ky/kx values.

4 Conclusions

This study investigated the effect of several different vertical sand drain parameters on the behavior of an earth dam constructed on soft clay in northeastern Iran. At a given time, with increasing depth and diameter of the vertical drains, the rate of consolidation settlement of the foundation increases with respect to no drain condition. The settlement ratio increased up to 90% related to the total final settlement (0.9 m) within 24 months due to the increase in pore water dissipation. In fact, this situation decreases the duration of the foundation improvement.

With improvement of the foundation by vertical drains, the safety factor is increased both upstream and downstream. The FS increase is in a gradual gradient up to > 2 while FS is at < 1.5 in no drain condition. Among the different studied drain parameters (spacing, depth and diameter), the drain spacing is the most significant parameter that affects the settlement and factor of safety. The research also showed that along with a decreasing ratio of vertical-to-horizontal permeability (ky/kx), a lower ky/kx value (0.1), as in field conditions, contributes to lower settlement rate values and upstream and downstream safety factor values, up to about 80%, with respect to time and drain depth change.

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